Bringing ROCOF into spotlight in Smart Grids: new standardization and UFLS method

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Abstract

The development of Smart Grid applications in electric power systems has highlighted larger frequency variations and disclosed misunderstandings related to frequency and its derived quantities. This paper discusses the mathematical and physical background behind frequency variations in the electric power system and the contribution of International Electrotechnical Commission (IEC) in standardizing the performances of frequency and frequency- related protection relays. Last but not least, the paper brings the focus on frequency-related measurements (frequency and its rate of change) with a new concept for underfrequency load shedding's decisions which is expected, thanks to its simplicity and intuitive design, to contribute to the frequency stability in electric power systems.

Keywords

synchronous machines, rotation speed, voltage frequency, Rate-of-Change-of-Frequency (ROCOF), frequency, protection, testing, IEC 60255-181, Smart Grid.

Nomenclature

ΔT	synchronous machine acceleration torque
$\dot{\omega}_{\mathrm{SM}}$	synchronous machine rotor acceleration
Θ_{REF}	synchronous machine rotor-angle reference
a	synchronous machine rotor speed ramp rate
A	value of the induced voltage amplitude
AC	alternating current
COI	Center of Inertia
EPS	Electric Power System
f_{LIM}	selected frequency-stability limit
f_{r}	rated electrical frequency
H	synchronous machine inertia constant
H_{COI}	equivalent inertia constant of the entire EPS
IEC	International Electrotechnical Commission
$M(t)$	frequency-stability margin
n	measuring sample consecutive number
PMU	Phasor Measurement Unit
RES	Renewable Energy Resource
ROCOF	Rate Of Change Of Frequency
SM	Synchronous Machine
Smart Grid	Electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as: *i*) to integrate the behaviour and actions of the network users and other stakeholders, *ii*) to efficiently deliver sustainable, economic and secure electricity supplies ([1])
t	time
T_{e}	the electro-magnetic torque of the SM
T_{m}	the mechanical torque on the SM's shaft
TSO	Transmission System Operator
$u(t)$	induced voltage at SM terminals
UFLS	UnderFrequency Load Shedding
δ_{SM}	SM rotor-angle
ω_{r}	rated angular speed of the SM

I. Introduction

In the last decade, the frequency concerns related to electric power systems (EPSs) became a popular topic again, which can be confirmed by both the amount of published research publications on the subject and financing of large international projects (e.g. MIGRATE [2]). For a long period of time after merging individual (national) EPSs into vast interconnections by building multiple tie-lines, EPS frequency was basically a constant value all across the system and therefore not a source of any worries for transmission system operators (TSOs). Reasons for coming back to discussions about frequency are to be sought in the EPS developing trends, especially those related to the on-going increase in the amount of renewable energy sources (RES) penetration, all of them being closely connected to the concept of Smart Grid ([3]). A significant indicator of this situation is given by the IEC protection functional standards as well, in particular IEC 60255-1xx series. In Fig. 1, an example of effective and operating ranges for distance protection function is provided, published in IEC 60255-121 [4], 2014. On the other hand, in new IEC standard for differential protection IEC 60255-187-1 (foreseen to be published in 2020), the frequency and operating ranges are much larger than those in Fig. 1, because of the feedback received from the protection community on wider power frequency deviations due to Smart Grid applications (Fig. 2).

Quantity	Effective range	Operating range
Current	20 % to 1 000 % of rated current	20 % to 4 000 % of rated current
Voltage	5 % to 150 % of rated voltage	2 % to 200 % of rated voltage
Frequency deviation	-2 % to +2 % of rated frequency	-5 % to +5 % of rated frequency

Fig. 1. Example of effective and operating ranges for distance protection in IEC 60255:121:2014 standard, from IEC 60255-121:2014 ed.1.0, “Copyright © 201x IEC Geneva, Switzerland. www.iec.ch”

Conventional generation fleet involves large power plants, where the primary energy source (coal, gas, water, nuclear) is converted into electrical energy by big synchronous machines (SM). The installed capacity of these machines is in the range from tens, hundreds and even thousands of megawatts. For a SM to successfully generate the alternating voltage at its terminals, it needs to spin. A side product of spinning is an inherent storage of a certain amount of energy in the form of rotating kinetic energy, i.e. inertia. The larger the quantity of energy stored in the rotating rotor of the SM, the larger the inertia is. This enables to automatically compensate any sudden variations in the electrical consumption by withdrawing the stored energy from the SM rotors, which in turn means their deceleration. As a result, the alternating voltage at machine terminals is also induced with a lower frequency.

Input Energizing quantity	Effective range	Operating range
Current	0% to 1000% of rated current	0% to 4000% of rated current
Voltage	5% to 150% of rated voltage	2% to 200% of rated voltage
Frequency deviation(1)	-5% to +5% of rated frequency	-10% to +10% of rated frequency

Fig. 2. Example of effective and operating ranges for differential protection in the coming IEC 60255:187-1 standard

Until recently, most of the generating power/energy was supplied by the described conventional units. The total EPS inertia was large and the speed of SM was less seriously affected by sudden consumption changes. However, a massive integration of RES significantly affected EPS inertia (and continues to do so), since they are based on power electronic converters. The alternating voltage in RES is generated in the converters by providing appropriate control. This means that in contrast to conventional SMs, their response to EPS events is no longer inherently achieved. On the contrary, the RES control is purely active. Total EPS inertia is therefore decreasing, leaving less stored energy in the rotating masses of large SMs. This means their faster deceleration/acceleration for the same amount of active power imbalance. The increasing importance of frequency-related protection functions in modern EPSs brought to a large number of frequency and ROCOF relays installed, many of them implementing different methods and algorithms to measure the EPS frequency and its rate of change. Several events with missed/unwanted operation of those relays [5], together with the increasing use of those protections for Smart Grid applications, generated the need to have a functional IEC standard for assessing the behaviour of frequency-related protection functions in an unequivocal way ([4], [7]).

In this paper, some important background information on the term *EPS frequency* is provided, since it is often used in the power engineering community without understanding what it actually means and what kind of processes lie behind it. This paper will help to understand that the electrical voltage frequency is merely a consequence of mechanical rotating speed of synchronous generators within EPS. This will be supported by presenting a simple yet effective underfrequency load shedding concept based on ROCOF. Compared to the existing concepts, it provides a high level of adaptability by taking advantage of local ROCOF oscillations after faults. In addition, its operation and settings are generalized and no customizations are required in different EPSs. Finally, the paper will address the IEC standardisation concepts for frequency and rate of change of frequency (ROCOF) in the world of protection described in the latest IEC standard for frequency related protection functions IEC 60255-181:2019 [4].

II. Source of Electrical Frequency

In our everyday life, power engineers often use the expression *measuring the frequency*. In contrast to signal processing in other fields of electrical engineering, electrical-voltage frequency originates from the interaction between complex power plants (among others involving SMs) and the electrical grid. So, one often forgets that *frequency measurement in the EPS* is merely a process that was introduced for *estimating* the average angular speed of SMs at a particular instant. In this section, it will be discussed how the angular speed of individual SMs is affected by active power imbalance in the EPS and that it is not a simple task to always accurately assess the frequency, since it is not a global system parameter outside stable, steady-state operating conditions.

A. A swing equation

A swing equation is a mathematical formulation of the SM rotor-angle δ_{SM} behaviour after being exposed to a torque imbalance [8]:

$$\frac{2 \cdot H}{\omega_r} \cdot \ddot{\delta}_{SM} = T_m - T_e \qquad (1)$$

where H represents the inertia constant in s, ω_r rated angular speed of the machine in rad/s, δ_{SM} the rotor angle of the machine relative to the selected reference in radians, T_m the mechanical torque on the SM's shaft and T_e the electro-magnetic torque of the SM (see Fig. 3), both in p.u. Please note that for the sake of simplicity, the damping of the machine was ignored in (1). Any imbalance between T_m and T_e (referred to as the *accelerating torque,* or *net torque,* ΔT) leads to a dynamic change in δ_{SM}. At this point, it is important to note that the SM rotor speed ω_{SM} and the SM rotor acceleration $\dot{\omega}_{SM}$ equal the first and the second time-derivatives of the rotor angle δ_{SM}, respectively:

$$\dot{\delta}_{SM} = \omega_{SM} \quad , \quad \ddot{\delta}_{SM} = \dot{\omega}_{SM} \qquad (2)$$

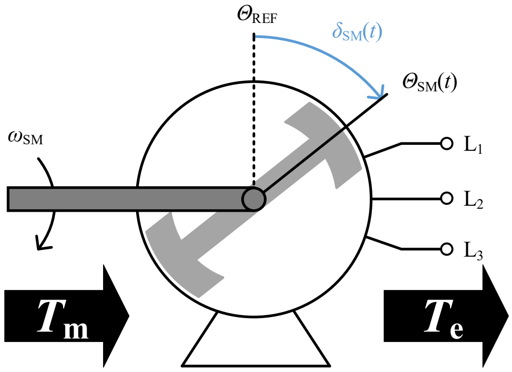

Fig. 3. A conceptual representation of a synchronous machine

In large EPSs, the electrical energy generation is performed by many SMs at the same time, each one of them being a subject to (1) with its own parameters and torque balances. Therefore, depending on the location within the EPS, where the sudden power imbalance event originates, SMs generally experience different accelerating torques since they are both geographically as well as electrically not equidistant away. The distribution of accelerating torques among all SMs in the network follows the laws of power flow equations, in this particular case referred to as the *synchronizing coefficients*. This was extensively discussed and explained in [8] and [9].

In the past, the occurrence of a significant active-power imbalance was typically associated with a sudden absence of conventional generation, as synchronous generators might have been tripped by protection relays dedicated to eliminate a power system fault. On the other hand, the development of EPSs in terms of Smart Grids, which strongly relies on the distributed energy sources, increases a possibility for sudden power imbalances even further, since large portions of total power generation strongly depend on local weather changes ([10]). For example, up to 90% of the solar power production in a region can be lost in a few seconds because of the clouds. Such systems are also characterized by a very low (if not zero) inertia [11].

Therefore, after active power imbalance in the network occurs, not only that individual SMs are a subject to different accelerating torques ΔT, they are also of different constructions, i.e. they have different inertia H. As a result, their speed changes with different rates, which is followed by inter-generator oscillations. Dynamic simulation of this phenomenon is shown in Fig. 4 for a three-SM case (IEEE 9 bus test system, simulated with PSS Netomac). Fig. 4a illustrates an oscillating response of SMs (for SM speed oscillation, observe the zoomed part of the figure). However, it is important to note that compared to the SM rotor speed, rotor acceleration (Fig. 4b) exhibits differences in SM responses much more clearly and evidently.

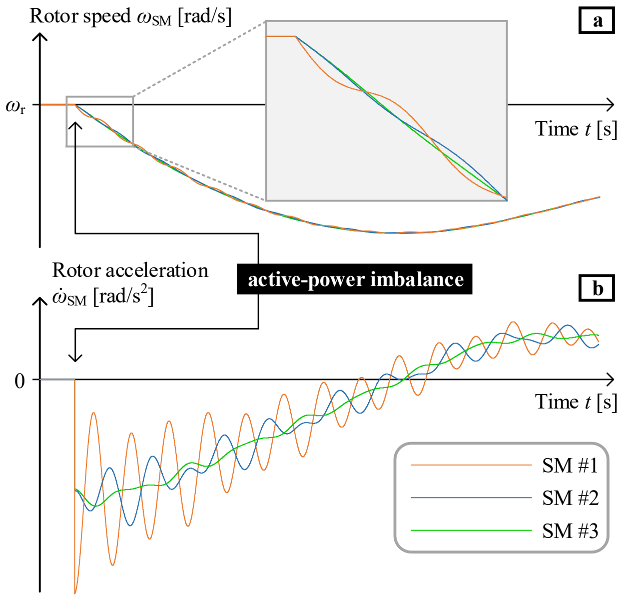

Fig. 4. Rotor speed (a) and acceleration (b) of different SMs in the network following an occurrence of an active-power imbalance

B. Non-distorted AC voltage frequency

Within the transmission network (e.g. in the substation), a direct access to instantaneous rotor speed values of all SMs in the network is impossible in real time. Therefore, one is forced to make a compromise and try to estimate it *indirectly*. The input to the estimation procedure consists of electrical signals, available in the substation location, i.e. AC voltage and AC current. It is important to note that these electrical quantities are often a subject to several electro-magnetic transients and therefore do not offer the most appropriate set of input signals for the frequency estimation. Unfortunately, for protection purposes such as under-frequency load shedding (UFLS), these conditions usually coincide with moments when the accuracy of the rotor speed estimation is most needed.

Originating in Fig. 3, a rotor angle of the machine can be determined only after the angle reference is clearly defined. In this situation, the angle reference Θ_{REF} is set vertically, as shown in Fig. 3. The instantaneous position of the rotor is denoted by $\Theta_{SM}(t)$, providing the rotor angle $\delta_{SM}(t)$ as the difference between both:

$$\delta_{SM}(t)=\Theta_{SM}(t)\text{-}\Theta_{REF} \qquad (3)$$

For the sake of simplicity it seems reasonable to select $\Theta_{REF} = 0$. The most simplified expression for the induced voltage at SM terminals is therefore:

$$u(t)=A\cdot\sin\big(\delta_{SM}(t)\big) \qquad (4)$$

where A represents the p.u. value of the voltage amplitude. The sine-function argument is therefore the rotor angle. In order to appropriately model any changes in the rotor speed, the rotor angle has to be considered as its integral:

$$\delta_{SM}(t) = \int \omega_{SM}(t)\, dt \qquad (5)$$

For reader's convenience, it is reasonable to provide further expressions separate when:

– the rotor speed is constant (equal to ω_r):

$$\delta_{SM}(t) = \int \omega_r \,\mathrm{d}t = \omega_r \cdot t \quad (6)$$

$$u(t)=A\cdot\sin(\omega_r \cdot t) \qquad (7)$$

– the rotor speed is ramped downwards from the rated value with rate a due to a sudden active power deficit in the EPS (as a consequence of either tripping of large conventional generating units or local weather changes and fast decrease of renewable generation):

$$\delta_{SM}(t) = \int (\omega_r - a \cdot t)\,\mathrm{d}t = \omega_r \cdot t - a \cdot \frac{t^2}{2} \qquad (8)$$

$$u(t)=A\cdot\sin\left(\omega_r \cdot t - a \cdot \frac{t^2}{2}\right) \quad (9)$$

Graphically, the situation is shown in Fig. 5. The solid black curve depicts the situation with a constant rotor speed $\omega_{SM} = \omega_r$ during the entire simulation – see Fig. 5b. Fig. 5a shows a corresponding linear increase in the rotor angle according to (6) and Fig. 5c - zero rotor acceleration. The thick blue line, on the other hand, depicts a situation with a ramp down of the rotor speed from steady-state 50 Hz, which lasted first two full rotations (from t = 0 s up to t = 0.04 s), to a value that corresponds to

48 Hz. This happens in exactly 0,4 s. The presented case with a “frequency ramp” of a = -5 Hz/s corresponds to the most extreme ramping value that is foreseen by IEC 60255-181.

C. AC voltage frequency measurement

After reading section II.B, one should be aware of the fact that engineers are forced to estimate the SM rotor speed via an alternating voltage or current. In step one, an *estimate* of the AC signal frequency is performed either by any of well-known methods (such as e.g. by a well-known method of zero-crossing detection) or by any alternative methods, which are under intellectual property rights of individual relay/PMU manufacturer [12] or subjects of research for new algorithms ([13] and [14]).

If we take a simple zero-crossing method as a representative example, one firstly has to define the reference phase-angle of an AC signal. In [8] it is suggested that detected zero-crossings should be provided with the relation to the AC signal with the nominal (synchronous) frequency. In order to make this more clear, Fig. 6 depicts a concept together with denoted zero crossings and measured phase-angles δ. It is clear that during the frequency ramping, the consecutive phase-angles are increasing with time, whereas during the constant frequency periods, they remain constant. It is therefore not difficult to write an expression for the frequency:

$$\omega(t)=\omega_{\mathrm{r}}+\frac{\mathrm{d}}{\mathrm{d}t}\delta(t) \qquad (10)$$

or in more commonly used Hertz (Hz) terms:

$$f(t)=f_{\mathrm{r}}+\frac{1}{2\pi}\frac{\mathrm{d}}{\mathrm{d}t}\delta(t) \qquad (11)$$

where f_{r} denotes the rated electrical frequency in Hz.

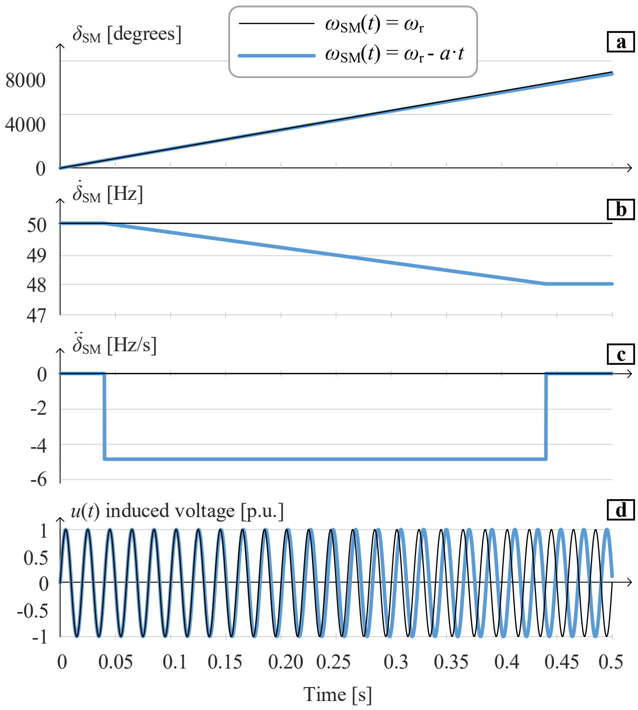

Fig. 5. Rotor angle (a), rotor speed (b), rotor acceleration (c) and generated induces voltage (d) during constant angular deceleration

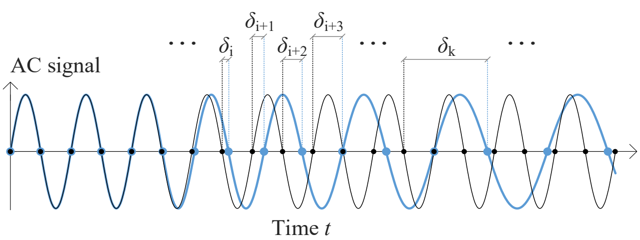

Fig. 6. Zero-crossing detection process

Clearly, phase-angle measurements in Fig. 6 are discrete, so in practical applications, (10) and (11) have to be adjusted, considering derivative as a ratio between the difference among two consecutive angle samples $\delta(n)$ and $\delta(n$-1) and the time interval ΔT:

$$f(n)=f_{\mathrm{r}}+\frac{1}{2\pi}\frac{\delta(n)-\delta(n-1)}{\Delta T} \qquad (12)$$

The same goes for the calculation of ROCOF:

$$ROCOF(n)=\frac{f(n)-f(n-1)}{\Delta T} \qquad (13)$$

The latter is gaining a lot of attention both in the academia as well as industry lately, since it reflects the active power imbalance in the system. Positive ROCOF indicates acceleration of SMs due to excess of active power generation, whereas negative ROCOF indicates deceleration of SMs due to lack of active power generation. However, by looking at (1) it is clear that without good information about the involved inertia in the system, ROCOF does not provide any more information about the power imbalance other than its sign. Also, the entire process described in this section explains why there is often a high level of scepticism present when considering ROCOF-based protection functions: correctly set ROCOF requires good system studies that are not easily manageable by everybody. On the other hand, when one is fully aware of the entire background regarding ROCOF, it can still represent a strong benefit and regain the trust of engineers. Also in IEC, the Technical Committee 95 has recently decided that frequency and frequency-related protections are the most important functions to be considered for the protection of the Smart Grid. This decision brought to the development of the new standard IEC 60255-181:2019 with a very high priority. This is why in section III, one innovative way to combine frequency and ROCOF measurements for the purpose of UFLS is briefly summarized.

D. Interest in the speed of synchronous machines

Conventional EPS grid codes usually restrict the electrical frequency to a relatively narrow band around its nominal value [16]. The intention of this subsection is to identify two most evident reasons for the existence of this restriction. According to the available literature, it can be recognized that both are related to steam and gas turbines.

Excessive vibrations of turbine blades

Different segments of steam and gas turbines are a subject to various pressures and this is why they consist of differently dimensioned blades. As a result, these turbine blades have different resonant frequencies. When exposed to the injected medium, the turbine spins and the blades are deformed due to several forces occurring during the spinning. As a result, their resonant frequencies are varied as well, depending on the speed of the turbine. During the turbine construction phase, blades are designed so that their resonant frequencies are sufficiently displaced from the rated speed (and its multiples) of the turbine. When operating at off-nominal speed, resonant frequencies might be stimulated, causing mechanical stresses that is accumulated in time [17].

Excessive heating of gas-turbine blades

When the speed of the gas turbine is decreased, the airflow to its combustion chamber is reduced since the compressor slows down as well. Consequently, the fuel to air ratio in the combustion chamber increases and so does the exhaust gas temperature [18]. As a result, excessive heating of the blades can cause the deformations, which is again the reason for potential interaction with stimulated frequency.

III. Using Rate-of-CHange-of-Frequency for Under-Frequency Load Shedding Protection

In section II it was explained that there is a linear relationship between the accelerating torque on the SM and the second time derivative of its rotor angle: this relationship is the moment of inertia. The latter tightly relates to ROCOF, calculated from the electrical AC signals. One might advantageously use this finding by choosing certain assumptions when deriving an equivalent swing equation for the entire multi-machine EPS (the entire derivation is provided in [8]):

$$\frac{2 \cdot H_{\mathrm{COI}}}{\omega_{\mathrm{r}}} \cdot \ddot{\delta}_{\mathrm{COI}} \approx \Delta \mathrm{P} \qquad (14)$$

where the notation COI refers to the Center of Inertia. This term is used for the representation of a fictive, equivalent SM, which speed corresponds to a weighted average of speed values of all involved SMs in the network. In (14), H_{COI} represents the equivalent inertia constant of the entire EPS in s, ω_{r} rated angular speed of the equivalent machine (COI) in rad/s, δ_{SM} the rotor angle of the equivalent machine (COI) relative to a selected reference in radians and ΔP the active power imbalance that aggravates the EPS as a whole. The latter is in p.u., based on the sum of rated powers of all machines in the EPS. From what we explained so far, it should be clear why (14) is often used by the engineers within connection with ROCOF. Equation (14) presents a very tempting path towards figuring out the amount of power imbalance that should be handled by frequency control or UFLS protection. However, apart from the challenge of measuring the average ROCOF, the estimation of inertia H_{COI} is an enormous challenge by itself. Such approach was critically judged in previous publications ([9], [19]).

Once an active power imbalance occurs in the EPS, instead of looking back in time to find out the details about the past event, [20] represents a completely different approach by setting the focus in the upcoming future. Assuming the power imbalance is kept unchanged for several upcoming seconds (which is appropriately a worst-case scenario), one can estimate the remaining time $M(t)$ before frequency will reach the selected limit f_{LIM}. In this way a so-called *frequency-stability margin* is estimated that is a good indication on how fast UFLS should react. If one is dealing with a large safety margin $M(t)$, frequency instability is expected far ahead in the future due to very small ROCOF. Therefore, UFLS activation is not yet required which makes this a *frequency-control problem* (see Fig. 7). On the other hand, a small safety margin $M(t)$ indicates that frequency-stability is about to occur soon (either by the frequency already being low or ROCOF is high), so an immediate intervention of UFLS protection scheme is required. Therefore, a frequency-stability margin can be used for differentiating between frequency control and protection problems in real time.

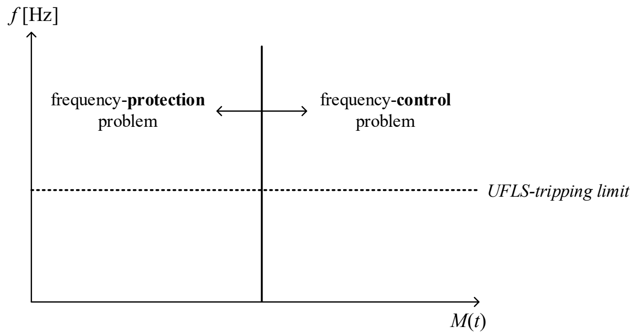

Fig. 7. Frequency-stability margin $M(t)$ might help to differentiate between the frequency-control and frequency-protection problems

In Fig. 8, an example of an operating point trajectory in a frequency $f(t)$ versus a frequency-stability margin $M(t)$ diagram is depicted, after the EPS is a subject of a sudden active-power imbalance. Red and green curves represent EPS response following two different power-imbalance conditions. In a green-curve example, large $M(t)$ values indicate a very slow-acting frequency drop and as a result, UFLS tripping was delayed since there is evidently more than enough time for the frequency control to effectively pick up the frequency. On the other hand, a red-curve example indicates a fast-acting frequency decrease and therefore the UFLS is required to activate as soon as the pre-set frequency threshold is violated.

Following this line of thinking, [20] suggests to upgrade a single-criterion UFLS into a double-criteria UFLS. In parallel to already existing frequency-threshold violation as an existing criterion, authors suggest adding another criterion in terms of $M(t)$ – a so-called *frequency-stability margin criterion* defined by M-threshold (see Fig. 8). This simple modification brings another dimension to the conventional UFLS, which might be described as analogy to inverse-time characteristic in overcurrent protection. On one hand, such approach provides intuitive interpretation of EPS frequency conditions and the transparent use of ROCOF, on the other hand. More details of this approach are provided in [20], whereas in [21] the approach was hardware-in-the-loop (HIL) tested with RTDS simulator at the University of Ljubljana.

At this point, it is reasonable to list the advantages of the described UFLS. *First*, existing literature treats intensive local ROCOF oscillations following a power-imbalance incident as a negative aspect. Presented approach does quite the opposite. It recognizes and utilizes the potential of these local oscillations. Using ROCOF causes non-synchronized relay operations for achieving a more accurate power rebalancing. *Second*, it is extremely robust, since its operation is (same as conventional UFLS) based purely on locally obtained measurements. There is no need for establishment of any kind of communication between the relays, which may contribute to decreased reliability. *Third*, it introduces a high level of flexibility to UFLS despite the simplicity and transparency of the concept. In fact, the representation of real-time conditions in a f-M diagram creates an analogy to distance protection relay settings (e.g. polygon characteristic). *Fourth*, the implementation of additional criterion to microprocessor-based relays is simple and fast, requires only a software update. At the same time, the implementation can be gradual without a hazard for system security, which is especially important for EPSs with a large share of electromechanical relays. *Fifth*, it better complies with the pure definition of UFLS compared to most other UFLS. It concentrates on stopping the frequency decay and leaves the frequency control to bring it back within desired limits. Other methods combine those two functionalities, which is in our opinion undesired.

IV. IEC Standardisation for Frequency-Related Protection Functions: IEC 60255-181:2019

Since February 2019, a new relay protection standard IEC 60255-181 is valid, specifying relay performances and test methodologies for frequency and ROCOF relays. The IEC 60255-181 standard was created with the focus on new protection requirement for the Smart Grid. As the targeted protection functions are commonly implemented in one or more protection relays, it is expected that the standard covers the protection functions when they are hosted in the "traditional" protection relay. Nevertheless, it is very important to mention that the standard also applies to such functions when they are embedded in different devices forming a Smart Ggrid, as such as the inverters powering the grid from distributed generators or trip units in low-voltage circuit breakers.

Customers and users should expect to receive a type test report and performances declaration from the manufacturer of these functions according to the IEC 60255-181 for those implementations which are "hidden" in devices that are not commonly considered protection relays, but that do perform a relay protection task and operate a circuit breaker (electromechanical or static).

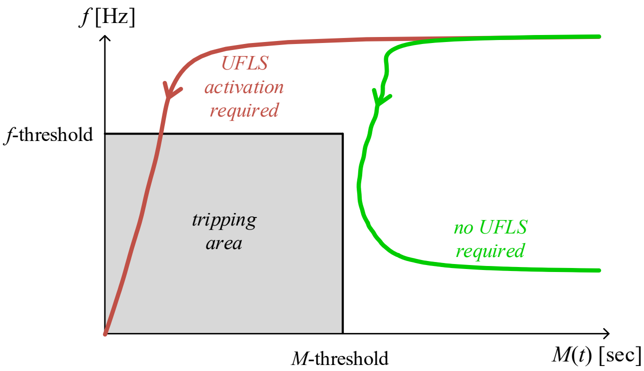

Fig. 8. Using frequency-stability margin $M(t)$ for setting the UFLS tripping criteria

One of the most important aspects of IEC 60255-181 is standardization of realistic conditions to be applied to the protection function when assessing many performances related to dynamic behavior of an EPS.

The use of a standardized formula to represent this dynamic behavior wants to minimize important misunderstandings related to the start time and/or operate time of the protection relay. The relay community has unfortunately experienced situations when frequency and ROCOF relays from different manufacturers, connected to the same busbar voltage and with the same settings (overfrequency, underfrequency or ROCOF thresholds) performed quite differently from each other: some of the relays did not start at all for the event, the second ones did start but tripped much faster than expected, the third ones started and tripped much slower than expected [5].

IEC 60255-181 contains the minimum requirements for protection relay type testing; so it is not a standard for maintenance/commissioning applications. It is important to understand it in order to be able to correctly apply the definitions for commissioning and maintenance testing.

The way the frequency varies is defined by the normative annex A: “Test signal equation with constant frequency variation (df/dt)”. This ramp shall follow the explicit mathematical formula that is shown in Fig. 9 and that is in practice the explicit integral of (1) and very similar to (9).

This waveform is automatically generated by real-time simulation programs for EPSs, as numerical solution of the electromechanical equations based on (1), but simple relay test equipment to assess the relay functionality according to the standardized formula was not available when the standard was developed. Now, ([22]) and many more will come, contributing to a more reliable protection of the EPS.

Before the standard, there were many different methods to generate a frequency ramp, and depending on the method used, the test result was different. This is definitely one of the causes of unwanted trips. Many relays have been tested with non-standardized methods that “confirmed” correct behavior, but the methods were not realistic enough and this generated surprises when a real power system event occurred.

Annex A
(normative)

Test signal equation with constant frequency variation (*df/dt*)

The equation for the signals used to perform the test of frequency and ROCOF functions with a constant variation of the frequency is specified below.

$$G(t) = \mathrm{Amp} \times \sin\left(2\pi\left(f_0 + \frac{f\_\mathrm{slope}}{2}(t - t_0)\right)(t - t_0) + \varphi_0\right)$$

where

- Amp is the peak amplitude of the input energizing quantity/quantities (for example, phase voltage);
- f_0 is the initial frequency (for example, nominal frequency, before the frequency change);
- f_slope is the frequency slope in Hz/s used for the test;
- φ_0 is the initial phase (used for the test with three-phase voltage injection);
- t_0 is the beginning of the frequency variation.

Fig. 9. The mandatory equation according to IEC 60255-181 for the formula generating the frequency changing signal (“frequency ramp”)., from IEC 60255-181:2019 ed.1.0, “Copyright © 201x IEC Geneva, Switzerland. www.iec.ch”

The waveform generated by the formula in Fig. 9 can be described as a waveform with a stepless (continuous) change of frequency. At any time instant, the frequency changes. No other methods to “reconstruct” or “simulate” the standardized waveform are allowed. For example, some methods used in the past have tried to simulate the frequency ramp by changing a signal frequency at each period. This is a discrete change of frequency (not stepless) and it is not allowed, in order to have the same test method for all relay manufacturers (Fig. 10 and Fig. 11) [5].

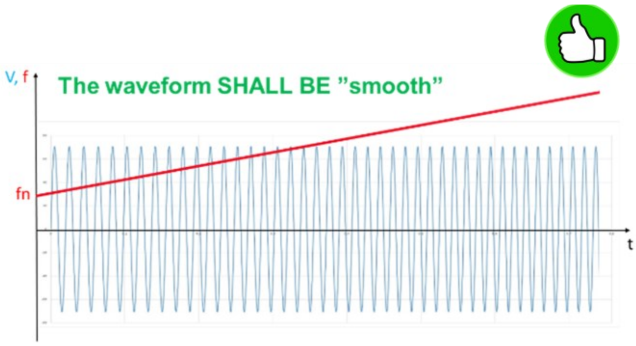

Fig. 10. Graph of the “stepless” (continuous) frequency ramp used to assess ROCOF and frequency relay performances

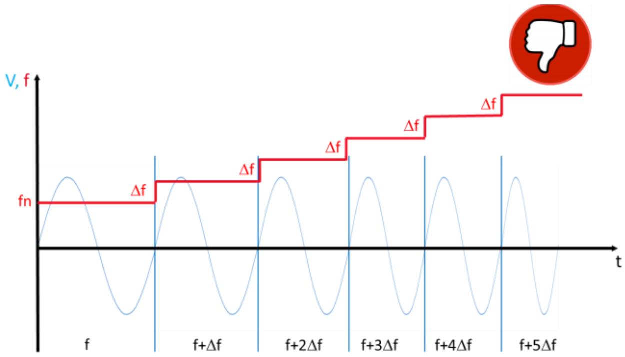

Fig. 11. Graph of a non-“stepless” (continuous) frequency ramp. This ramp is not allowed. Depending on the size of steps and relay algorithms, different results may be obtained for the same relay.

An obvious difference in using the standardized approach (Fig. 10) or not (Fig. 11) is as simple as this statement: if a protection relay (ROCOF, overfrequency or underfrequency) behaves “strangely” while using the standardized approach, it is worth to investigate and involve the relay manufacturer. If other “strange results” are noted while use of any non-standardized approach, nothing can be said. On the contrary, if expected results are given by the standardized approach, we are sure that more than those tests could not have been done and probably the relay will behave correctly once in service. If expected results are obtained by using the non-standardized approach, it is known that this is no guarantee for any correct behavior, once the relay is in service ([7], [23]). IEC 60255-181 standard contains many more definitions and tests than those presented in this paper. The focus was on the standardized “frequency ramp” as the concept is definitely ambitious and new.

V. Conclusion

In this paper, the authors established that in Smart Grids, frequency and frequency-related protections are the most important functions to be considered. This is the main reason for issuing IEC 60255-181:2019 standard, which specifies relay performances and test methodologies for frequency and ROCOF relays. Regarding the overall status of technology in the field of UFLS protection, known solutions applied to ROCOF still need some further development. Advancements are especially needed in terms of enhanced transparency and simplicity of solutions, since complex approaches are much less acceptable in practice. The authors briefly presented one of such UFLS attempts, which just passed a hardware-in-the-loop investigation with RTDS simulator that confirmed the proof of concept.

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